Integration of Structural Health Monitoring (SHM) into Multilayer Statewide Bridge Maintenance and Management Practices – SHM-Facilitated Condition-Based Maintenance (SHM-CBM) Prioritization System

Final Report
September 2018

BRIDGE ENGINEERING CENTER

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16. Abstract

For this project, the researchers developed a new structural health monitoring–facilitated condition-based management (SHM-CBM) maintenance prioritization system. This system represents an important step toward more widely integrating SHM into practice.

The kernel of the proposed SHM-CBM system is establishing a ranking index for each bridge in a particular inventory that establishes a maintenance funding priority for each bridge. A higher ranking index value indicates a lower maintenance funding priority. The ranking index is computed using both National Bridge Inventory (NBI) and SHM data, as well as user inputs.

A case study of the I-80 Sugar Creek Bridge showed that replacement could be postponed by up to 37 years using SHM-CBM because the condition of the bridge was determined to be better than what was previously assumed. This potential extension of service life in combination with expected maintenance, repair, and monitoring costs were used in a cost-benefit analysis that showed SHM system implementation is financially justifiable.

The SHM-CBM approach has the following advantages over current decision-making approaches:

- Continuous and near-real-time SHM data are used in decision making
- Wide range of quantitative data can be gathered using SHM (e.g., strain and temperature, chloride infiltration, tilt, and corrosion)
- Reduced uncertainty regarding structural performance
- Elimination or reduction of over-maintenance and deterioration or failure due to a lack of information about a bridge's true condition

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EXECUTIVE SUMMARY

In light of the of state-of-the-practice limitations in bridge maintenance and management decision making, a new structural health monitoring-facilitated condition-based management (SHM-CBM) maintenance prioritization system was developed in this research. The development of this system is an important step toward more widespread integration of SHM into practice.

CBM is a maintenance strategy used to actively manage the condition of assets with the goal of performing maintenance only when it is needed and at the most opportune times. This maintenance strategy is still very new to the bridge management community. In fact, not until the appearance of bridge SHM systems could such a strategy be implemented, because currently collected bridge condition data are not sufficient for CBM strategies.

The kernel of the proposed SHM-CBM system is establishing a ranking index for each bridge in a particular inventory that establishes a maintenance funding priority for each bridge. A higher ranking index number means a lower maintenance funding priority. The ranking index is computed by using both National Bridge Inventory (NBI) data (i.e., the Inventory Index) and SHM data (i.e., the SHM modifier).

Results from a case study show that the replacement of Iowa’s I-80 Sugar Creek Bridge could be postponed by up to 37 years through the use of the SHM-CBM approach because the condition of the bridge was determined to be better than what was previously assumed. This potential extension of service life in combination with anticipated maintenance, repair, and monitoring costs were used in a cost-benefit analysis, which showed that the implementation of an SHM system is financially justifiable.

Compared to current decision-making approaches, the SHM-CBM approach has the following advantages:

- Continuous and near-real-time SHM data are used in decision making
- Wide range of quantitative data can be gathered using SHM (e.g., strain and temperature, chloride infiltration, tilt, and corrosion)
- Reduced uncertainty regarding structural performance
- Elimination or reduction of over-maintenance and deterioration or failure due to a lack of information about a bridge’s true condition

1. INTRODUCTION

1.1 Background

Bridges constitute the most expensive assets, by mile, for transportation agencies across the US and around the world. Most of the bridges in the US were constructed between the 1950s and the 1970s. Consequently, an increasing number of bridges are getting old and requiring much more frequent inspections, repairs, or rehabilitation to keep them safe and functional. In addition, due to constrained construction and maintenance budgets, bridge owners are faced with the difficult task of balancing the condition of their bridges with the cost of maintaining them. The Federal Highway Administration's National Bridge Inventory publication (FHWA 2014) lists, roughly, 539,059 open bridges without restrictions in the US. In addition, the inventory shows that 26,117 are structurally deficient, 71,908 are functionally obsolete, and 98,025 are totally deficient.

1.1.1 Bridge Management Systems

Bridge maintenance strategies depend upon information used to predict the future condition and remaining life of a bridge. The purpose of a future bridge condition assessment is to determine when to undertake repairs or maintenance to keep a bridge's condition within acceptable limits. Also, the estimation of residual or remaining life is an important input for budgeting and setting longer-term work priorities. To better manage bridge inventories, therefore, tools that can accurately predict the future condition of a bridge as well as its remaining life (i.e., when a bridge will become substandard in terms of load carrying capacity, serviceability, and/or functionality) are required. It goes without saying that having a strong and accurate understanding of the current condition of the structure is essential to estimating the future condition of the structure.

The American Association of State Highway and Transportation Officials (AASHTO) Manual for Bridge Evaluation (2016), used together with AASHTO's software programs PONTIS and BRIDGIT (2005), comprise the bridge management system (BMS) used by many states in the US. BMSs that accurately document the current and future condition of bridges are required by the 1991 Intermodal Transportation Efficiency Act (ISTEA) and the 1998 Transportation Equity Act for the 21st Century (TEA-21) for public safety. Even more, bridge owners are required to follow mandates in other bridge preservation areas that include inspection scheduling, cost analysis, and rehabilitation planning.

The Manual for Bridge Evaluation (AASHTO 2016) characterizes the condition of bridges across the US following highly prescribed processes and procedures. The components of a bridge are visually inspected biennially and the standardized four condition states (good, fair, poor, and severe) are assigned to each of the relevant components. The condition states are subsequently used to determine a bridge's condition, appraisal, and sufficiency ratings. These ratings then become an important parameter in the bridge management approach typically used by each state. Although the bridge condition states reflect deterioration or damage, they do not quantify the structural deficiency of a bridge or its components.

One approach to predicting the future condition of bridge components is to use a "back of the envelope" linear model that assumes one drop in deck condition rating every eight years and one drop in superstructure and substructure condition rating every 10 years. This approach has significant limitations in that it does not capture the actual aging process, nor does it reflect individual bridge differences in any way. Aging (Harman 1981, Mishalani et al. 2002) is the continuous accumulation of deleterious chemical and mechanical reactions (observed and unobservable) going on throughout the life of the bridge brought about by weather, service conditions (traffic, deicing, etc.), and their interactions. The linear deterioration model does not account for the nonlinear behavior brought about by the impact of traffic volume and weight, structure and material type, environmental impacts, and the interactions between these variables specific to any given bridge, and this might result in unreliable prediction of bridge future condition.

1.1.2 Structural Health Monitoring

The desire for many departments of transportation (DOTs) is to augment their existing inspection process and maintenance system with a system that can objectively and more accurately quantify the state of bridge health in terms of condition and performance, aiding in inspection and maintenance activities, and estimate the remaining life of its bridge inventory in real time. As early as the 1980s, bridge engineers have had the vision for an intelligent infrastructure system (Aktan et al. 1998, Connor and Santosuosso 2002, Connor and McCarthy 2006) capable of the following:

1. Sense its own load environment and its responses and identifying any ongoing damage and deterioration
2. Assess its condition regarding capacity and performance needs and the actual capacity that is being delivered
3. Determine if and when behavior thresholds are exceeded or compromised such that the structural capacity, traffic volume capacity, environmental limiting conditions, and others have exceeded predetermined criteria

In terms of alerts, the bridge owner is ideally alerted by the system when a diversion of traffic is required, when posting of the bridge is required to prevent infractions from accelerated deterioration, when bridge repairs are needed, and when the bridge needs to be closed. To this end, it has been identified (FHWA 1993, Civil Infrastructure Systems Task Group 1993) that one of the key requirements for an effective infrastructure management system is the establishment of structural health monitoring (SHM) systems capable of accurately and objectively predicting the health of the infrastructures' components and systems. It is also held by many researchers (Okasha and Frangopol 2012, Catbas et al. 2007) and the FHWA Long-Term Bridge Performance (LTBP) program (Ghasemi et al. 2009) that another important component is the establishment of indices or thresholds for the critical structural elements through, for instance, calibration of finite element analytical models that compute the measured strains, stresses, forces, reactions, and boundary conditions. In this conceptualization, the SHM system serves as the tool that enables a bridge owner to understand and evaluate the interactions between environmental conditions, bridge boundary conditions, bridge component mechanical conditions, and impacts of damage and deterioration on the mechanical characteristics of the bridge elements.

An SHM system traditionally consists of a network of monitoring sensors, data acquisition, and communication hardware and software for carrying out bridge condition assessments in real-time.

1.1.3 Bridge Maintenance Prioritization Strategies

1.1.3.1 State of the Practice of Bridge Maintenance Prioritization (FHWA 2011)

Corrective maintenance and preventive maintenance are the most common maintenance prioritization approaches utilized by most bridge owners. Sometimes these two approaches are combined using engineering judgement. For example, the Iowa DOT conducts a district meeting annually. In this meeting, DOT maintenance personal meet with district engineers, inspection crews, and maintenance crews to go through previously collected NBI data and to supplement inspection documentation for each bridge that has known defects, deterioration, or other concerns. A maintenance decision is then made based on the data and the judgement of the professionals in the meeting. This approach may optimize decision making to a certain degree; however, the decisions are still somewhat subjective because they rely on qualitative data and opinions that may or may not have inherent biases.

Within the corrective maintenance framework, a bridge is operated until a defect appears, then a decision needs to be made to determine if the defect is critical or non-critical. Prompt action is needed for critical defects. This approach has been used by bridge owners for years in prioritizing maintenance activities. However, some defects have developed that have gotten so significant that they were very expensive to fix and/or had safety threatening conditions. This approach is sometimes criticized because it does not use maintenance funding in an optimized way. In other words, some (minor) maintenance should be performed before severe damage can even occur.

Preventive maintenance includes periodic maintenance or maintenance based on condition prediction. This has fairly common use in the bridge community. It involves looking at the bridge’s rating history and available bridge deterioration models to find an optimized time for maintenance activities, but before severe failures occur. Due to limitations of currently available bridge deterioration models and the lack of quantitative data, accurately predicting the performance of a specific bridge is difficult, if not impossible. Therefore, preventive maintenance is still used more commonly for preventing severe failure rather than for optimizing maintenance activities. Even so, there is a cost associate with this approach. Generally, this strategy advises that maintenance be performed more often than is absolutely necessary and, as such, can lead to an over maintenance scenario.

1.1.3.2 Condition-Based Maintenance – State of the Art of Bridge Maintenance Prioritization Approach

Condition-based maintenance (CBM) (Cadick and Traugott 2009, Ni and Wong 2012) is a maintenance strategy used to actively manage the condition of assets/equipment in order to perform maintenance only when it is needed and at the most opportune times. CBM is accomplished by integrating all available data to predict the impending failure of assets as well as to avoid costly maintenance activities. This process depends largely on the ability of the manager or managing algorithm to recognize undesirable operating conditions as measured by diagnostic monitoring systems. The process also allows an asset to continue operating in an undesirable yet safe condition while it is being monitored until maintenance can be scheduled and then performed.

CBM can reduce maintenance costs, improve availability and reliability, and enhance asset life span. The strategy has been widely used in the management of weapon systems, nuclear power plants, jet engines, marine engines, wind turbine generators, natural gas compression, and others (IAEA 2007). However, the application to bridge management is limited because current bridge inventory data, which are collected biennially through scheduled bridge inspections, are not sufficient to implement CBM.

With the development of SHM, more and more bridges are being continuously monitored. By integrating the real-time or near-real-time bridge condition data collected by an SHM system into bridge inventory data, an SHM-facilitated CBM (SHM-CBM) framework is possible. Such a system is more fully developed by this research.

1.1.4 Financial Justification of SHM Instrumentation

With SHM instrumentation in-place, uncertainties associated with structural performance are reduced because bridge owners know the true performance of a structure in real-time or near-real-time. This will lead to postponed bridge replacement, delayed maintenance activities, and prevented bridge collapse. Taking these benefits into consideration, it is not difficult to justify the cost of SHM instrumentation.

1.2 Objectives

There are two major objectives of this work. The first objective is to develop a bridge maintenance prioritization system that integrates SHM techniques into current bridge management practices (technical integration of SHM into bridge management). Both the inventory data from biennial bridge inspections (i.e., inventory data) and real-time or near-real-time monitoring data from a new SHM system are used in the maintenance prioritization decision making. Due to the still somewhat limited availability of installed SHM systems, inventory data must still play a notable role in the maintenance decision-making process, with SHM data functioning as a “tuner” to refine the maintenance priority up or down to a reasonable and user-controlled degree when such data are available.

The second objective is to justify the SHM solution financially (financial integration of SHM into bridge management). Without being able to financially justify the additional cost associated with implementing an SHM system, it is very unlikely that widespread adoption will occur. There are many benefits to implementing a properly designed SHM system: increased service life, increased load carrying capacity, reduced uncertainty, and providing a tool for mitigating risk associated with an asset operating in the built world for many decades.

1.3 Organization of Report

In this report, Chapter 2 reviews a sample of current SHM systems and Chapter 3 details the SHM system, BECAS, which the Bridge Engineering Center at Iowa State University developed and is becoming more widely adopted. Chapter 4 describes the design and implementation of the proposed SHM-CBM system. Chapter 5 summarizes the financial justification for the adoption of SHM integration and presents a case study. Chapter 6 summarizes this work and presents several concluding remarks.

2. SAMPLE CURRENT INFRASTRUCTURE SHM SYSTEMS

2.1 Road Pavements

In pavement management systems (PMS), some owners use the pavement condition index (PCI) as the controlling factor for the scheduling of maintenance and repair (M&R) activities. PCI is a number between 0 and 100, with 0 being the worst condition. For instance, a PCI of less than 60 means the pavement needs reconstruction, while a PCI of greater than 80 or 85 means the pavement is in very good condition (NYSDOT 2010). The PCI is a function of road surface distress such as cracking, ride quality, structural capacity, and friction. The predictive variables for pavement condition in regression and deterministic mechanistic algorithms used in PMS include traffic loading, climatic conditions, pavement structural properties, and past rates of pavement deterioration. These algorithms are, in essence, mathematical tools that predict the time or cumulative traffic to reach a failure criterion. This information is then used to plan and schedule M&R activities for pavement systems.

2.2 Aerospace and Other Vehicle Systems

In the aircraft industry, one fleet asset management system is referred to as the integrated vehicle health management (IVHM) system (Ikegami and Haugse 2001). The goal of IVHM is to assess present and to predict future vehicle condition. This information is used to enhance operational decisions, support corrective actions, and plan subsequent continued use of the aircraft (Benedettini et al. 2009). In this framework, IVHM consists of four main blocks:

1. SHM systems to measure the state of the aircraft while in flight for damage prone stress concentration areas, for unanticipated aerial events such as impacts, and foraging effects such as fatigue and cracking, to establish the current state of the fleet. Structural health measurement is primarily through the use of fiber optic sensors for state parameter metrics such as strain, temperature, pressure load, and aircraft component accelerations. Probabilistic models for the stated parameters and failure models are also established at this stage (Xu and Lei 2012, Xu et al. 2013).

2. A prognostics and health management (PHM) block that uses the current stochastic state parameters together with damage growth characteristics to form failure probability models. This is followed by the calibration of a model to produce a probabilistic prognosis of damage evolution in terms of damage versus time or the number of cycles the aircraft is in use. The calibrated structural model can also be used to assess failure probabilities in areas not instrumented by sensors. If the failure probabilities established above are lower than the pre-set levels, the fleet of aircraft is kept in service.

   The processed structural damage parameters include strain time histories, power spectral densities, and root mean square (RMS) values of the state parameters. Because fatigue is the biggest problem in aircraft, the processed data are primarily used for designing repair patches with increased damping properties for installation on the aircraft body. These patches lead to reduced structural responses and, thus, extend the service life of the aircraft fleet.

3. Nondestructive inspections (NDIs) that are also used on aircraft while they are on the ground. When the probability of failure is higher than the pre-set levels, the fleet of aircraft is further subjected to non-destructive inspections, and, if needed, repairs are carried out at the aircraft maintenance facility.

4. Finally, an information technology (IT) block in the architecture for communication of the obtained knowledge base to the flight crew, operations and maintenance personnel, regulatory agencies, and the original equipment manufacturers (OEM).

Today IVHM is also applied to other types of vehicle systems, such as cars, trucks, ships, trains, helicopters, submarines, tanks, etc. In this broader sense, it describes an advanced system capable of carrying out health monitoring, diagnosis, prognosis, and computation of reactive planning decision-making tools for corrective and preventive measures for numerous components and subsystems, such as structural frame, engine performance, electronics, hydraulics, fuel systems, and electric power systems.

2.3 Tall Buildings

The issues of importance in tall buildings are the safety and comfort of the occupants. Tall buildings are normally designed using state-of-the art structural analyses coupled with wind tunnel testing on scaled models. Wind speed and direction are the primary parameters for wind tunnel prediction models. In this framework, the impetus for structural health monitoring is the need for establishing the accuracy and validity of the design methods. The results of the analyses must be in conformity with the monitored building performance (Kijewski-Correa et al. 2006, Kijewski-Correa et al. 2012, Kijewski-Correa and Kochly 2007, Kijewski-Correa and Pirnia 2007) as determined by sensors monitoring ground accelerations, damping, strains, deflections, gravity loads, and meteorological site conditions. From the SHM knowledge base, structural control in terms of limiting states is then established through the use of structural control devices such as active mass dampers (ADM), active variable stiffness (AVS) systems, hybrid mass dampers (HMD), and active gyroscopic stabilizers (AGS) (Kareem et al. 1999, Spencer and Nagarajaiah 2003).

2.4 Bridges

2.4.1 Current Bridge Management Systems

There are roughly 21 bridge management systems in the world (Adey et al. 2010). These management systems are used for the following purposes:

- Quantification of deterioration and performance indicators
- Formulation of corrective intervention strategies with respect to cost and time

- Quantification of changes following an intervention program

What all of these have in common is a lack of an integrated structural health monitoring system. Hence, they are all subject to the criticism of being subjective.

The general organizational structure of a bridge management system with an integrated SHM system is a self-contained entity comprising, at minimum, the following main features:

- Personnel consisting mainly of the scientific team, the technical team, and general staff
- The physical bridge
- Information technology
- Analytical division
- Decision-making wing
- Influence of the non-technical sector (Aktan et al. 1998)

All of the most advanced bridge management systems (e.g., PONTIS and BRIDGIT in the US (AASHTO 2005); NYSDOT in New York; OBMS in Ontario, Canada; QBMS in Quebec, Canada; KUBA in Germany) tend to use Markov probabilistic models based on linear transition probabilities that specify the likelihood that the condition of a bridge component will change from one state to another in a specified interval of time. These models have been found very useful in predicting the percentage of bridges in any given deterioration state, and in estimating the expected condition of a bridge at some given future time.

In the US, PONTIS is the bridge management system used by many states. With PONTIS, a bridge is subdivided into many structural elements instead of just the three components that have been the focus of historical National Bridge Inventory inspections (i.e., deck, superstructure, and substructure). Each element is evaluated separately and later combined at the project level to determine the best maintenance, repair, and rehabilitation (MR&R); improvement; and replacement strategy for the bridge.

PONTIS is a federally funded management system that uses probabilistic modelling techniques and optimization procedures coupled with the NBI database. The database is an accumulation of inventory, inspection, and supplemental data from traffic and bridge accident reports that are fed into PONTIS to help do the following:

- Predict deterioration for each bridge element
- Find the most cost-effective MR&R action to solve the deterioration problem
- Quantify any necessary functional improvements in terms of user cost and convenience and weigh them against the cost of MR&R
- Select the most appropriate bridge improvement and replacement
- Help in scheduling of the work to be undertaken using state-based statistical Markov models and solution methods that predict future bridge conditions.

None of the data in PONTIS come from a structural health monitoring system. PONTIS is, therefore, a subjective tool.

2.4.2 Implementation of an SHM Plan in BMS

The planned objectives for introduction of an SHM system are well known (i.e., to provide objective, quantitative data in real-time that can be used to assess structural damage, deterioration, and structural capacity and that can also be synthesized through algorithms to aid bridge owners in making decisions regarding bridge closures, posting, maintenance, repairs, and rehabilitation) (Rytter 1993). The actual process involves monitoring and capturing critical inputs and responses of a structural system. These system descriptors might include physical dimensional properties, strains levels, vibration properties, material properties, damping properties, and boundary conditions. Collectively, these inputs and responses can be used to understand the root causes of the problems as well as to track responses to predict the future behavior of a bridge.

There is no one SHM system that fits all bridges. A setting or application has to be defined for a SHM plan. Each bridge setting normally pre-determines a unique set of parameters to be measured and monitored so that a bridge may be accurately and completely characterized for reliable simulation.

2.5 Iowa DOT

The following two sections are a synthesis of the notes from a meeting between personnel from the Iowa State University Bridge Engineering Center and Iowa DOT Office of Bridges on January 28, 2016 in Ames, Iowa. The two sections describe the Iowa DOT's current bridge management system and a framework for a SHM-based bridge management system.

2.5.1 Iowa DOT Current Bridge Management System

According to the FHWA, bridges must be given a component condition rating and an overall sufficiency rating in accordance with the *Recording Guide for the Structure Inventory and Appraisal of the Nation's Bridges* (FHWA 1996). A component condition rating is an integer number between 0 and 9, with 9 representing a component in excellent condition and 0 representing a failed bridge that is out of service and beyond any corrective action. A bridge with a component condition rating of 5 or better is structurally adequate, requiring only cosmetic routine maintenance for minor section loss, cracking, spalling, or scour.

The Iowa DOT BMS is based on the biennial visual inspection reports generated and required to update the NBI database. These inspection reports, which include other levels of inspections deemed necessary by the Iowa DOT, include detailed descriptions of the type and extent of deteriorations observed by inspectors using photographs, construction drawings, and sketches. Bridge issues requiring immediate attention are also noted in the reports by the inspectors.

The Iowa DOT conducts around 2,500 bridge inspections annually. These inspections are most commonly completed using Iowa DOT personnel. Once each bridge inspection is complete, the inspection reports, together with the FHWA-required bridge inventory and the operating ratings provided by the Iowa DOT Office of Bridges and Structures, are used to prepare a Structure Inventory and Appraisal Sheet to comply with the FHWA biennial NBI reporting requirements. In addition, all bridge issues reported by inspectors as requiring immediate action are reviewed by the Iowa DOT Office of Maintenance. Based on the review, repair orders are issued to the district office with jurisdiction over the bridge. The Iowa DOT determines the type of repairs to be conducted and whether the repairs are to be done in-house or through a contract.

Bridges requiring contract-based repairs are entered into a five-year program of repair and replacement overseen by the Iowa Transportation Commission (ITC), although the commission cannot preclude a bridge from receiving repairs. Six times annually, the Iowa DOT conducts meetings to review and prioritize the bridges for repair and to determine the type of continued monitoring for those bridges that cannot be repaired with the current budget. A bridge repair ranking system has been developed by Iowa DOT for funding purposes. The ranking is based on the average daily traffic (ADT) and a number of issues with the bridge as reported by the inspector.

The Iowa DOT BMS is similar in many respects to what it was 25 years ago (Fanous et al. 1991). However, since 2014, the Iowa DOT has been developing a bridge element condition index classification system as well as a modified sufficiency rating formula for bridge elements. This sufficiency rating is used to help in the decision-making process when a large number of bridges are reported with varying element deterioration levels. One of the features the Iowa DOT is looking for in an SHM system, therefore, is the capability to help document the varying levels of deterioration in bridge elements.

2.5.2 Iowa DOT – Structural Health Monitoring Framework

The Iowa DOT, in conjunction with the BEC, has embarked on developing an SHM system to help collect on-site quantitative bridge measurements for use in its current bridge management system. The Iowa DOT's conceptualization of an SHM is a system that has the following characteristics:

- Generates significant bridge performance parameters and their thresholds that may assist in the Iowa DOT's current bridge management system. These parameters and thresholds, for the most part, will be dictated by or set in collaboration with Iowa DOT.

- Includes the rate of change of performance parameters for comparison with other bridges in the system.

- Allows users to query the system for specific bridge performance parameters at any time.

- Helps in bridge life-cycle cost computations, e.g., life lost while a bridge is awaiting repairs, knowledge of preventable part of lost bridge life, and annual loss of value of bridges in its inventory.

- Enables communications that go through personnel in the Iowa DOT Office of Maintenance.

In a strain-based SHM system such as the Bridge Engineering Condition Assessment System (BECAS) (see Chapter 3), the Iowa DOT has indicated a desire for a system that, at minimum, computes the following: strain and load rating time histories, strain/stress cycle accumulation, strain comparisons between bridges, and remaining bridge life. The Iowa DOT has also expressed an interest in a system that can monitor deck joints, quantify the corrosion of reinforced steel bars in the deck as a function of time, and evaluate bridge element condition states and the extent of bridge element deterioration.

3. BECAS ALGORITHMS AND AUTOMATED SOFTWARE

3.1 Introduction

The Bridge Engineering Center developed a structural health monitoring software package called the Bridge Engineering Condition Assessment System (BECAS). BECAS eliminates the subjectivity of current inspection approaches; increases evaluation frequency from once every two years to continuous; virtually removes human error, bias, and limitations; and provides feedback that can be used to perform proactive, rather than reactive, preventative maintenance. The following briefly describes the major components of BECAS, including the hardware and the software suite (BECAS Merge, BECAS Processing Engine, BECAS Damage Detection, BECAS Load Rating, and BECAS Distributor).

The BECAS hardware is comprised of off-the-shelf components integrated together to form a network of state-of-the-art sensors, data collection equipment, data storage, and an N-tier data processing hub. There are three sensor types that make up every BECAS installation: resistance strain sensors, temperature sensors, and GPS signal collectors. In addition, sensors of multiple types can be integrated into the system (tilt, deflection, corrosion, acceleration, etc.) depending upon any unique monitoring needs.

The sensors are connected to an on-site data logger that has integrated filtering capabilities. With read speed capabilities that approach 1,000 Hz, the data logger has the ability to collect the data needed (high-speed data collection is needed for vehicle identification and classification). On-board filtering capabilities added to each system help to ensure that measurement noise is minimized. To temporarily store, initially process, and then transfer the data to the main data processing hub, a mid-level desktop PC is connected to the data logger via wired Ethernet.

An IP-based video camera is also installed at each BECAS site. This camera is set up to record (and temporarily store) a live video feed of the bridge (including traffic crossing the bridge). One final key piece of the on-site hardware is an IP-based power switch. This power switch has multiple features that make it a useful part of the system. For example, the power switch allows remote users to power up or down individual system components from anywhere in the world. Second, in the event that the on-site system loses connection with the internet, the power switch automatically reboots the on-site cellular modem until the system comes back online fully.

Once transferred from the bridge to the office, the data are stored on a networked location. Then, an N-tier system of computers automatically detects the presence of new data and processes them. To create redundancy in the system and to provide a lower-cost method of analyzing the data in real-time, a typical BECAS processing architecture consists of a workstation-class PC (the parent) plus one or more lower-cost desktop PCs (the children). Even more, because currently available computers have multiple cores (i.e., processing threads), the BECAS software described in subsequent sections will parallel-process multiple files at once. Photographs of a typical field installation and a typical data processing cluster are given in Figure 3.1.

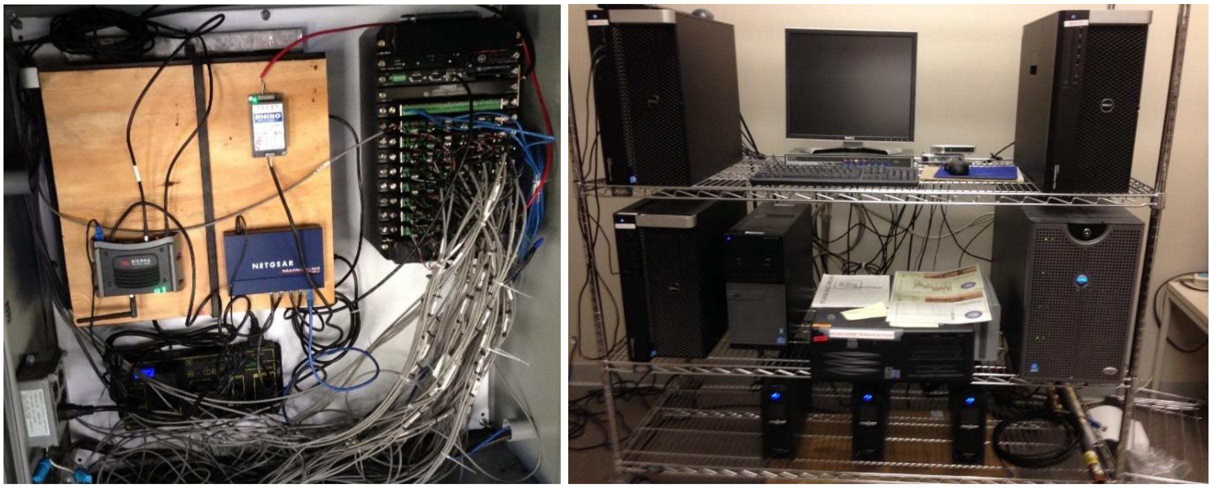


Figure 3.1. Typical field installation (left) and data processing cluster (right)

3.1.1 Bridge Description

In the following descriptions, a demonstration bridge is sometimes used to describe some aspects of BECAS. The demonstration bridge utilized here is FHWA #22380 on Interstate 80 in Iowa (see Figure 3.2).

Figure 3.2. Demonstration bridge FHWA #22380 on Interstate 80

The bridge is a 204 x 39 ft steel beam structure, built in 1966, carrying two lanes of I-80 eastbound traffic. The superstructure is a three-span, multi-beam continuous steel structure supporting a precast concrete deck overlaid with dense, low-slump concrete. The substructure consists of two end stub concrete abutments and two intermediate open-column concrete piers with cantilevers. The bridge is skewed 15 degrees right eastbound.

3.1.2 Bridge Instrumentation

The SHM system developed for the I-80 demonstration bridge consists of 71 strain gauges installed on the steel girders, as shown in Figure 3.3.

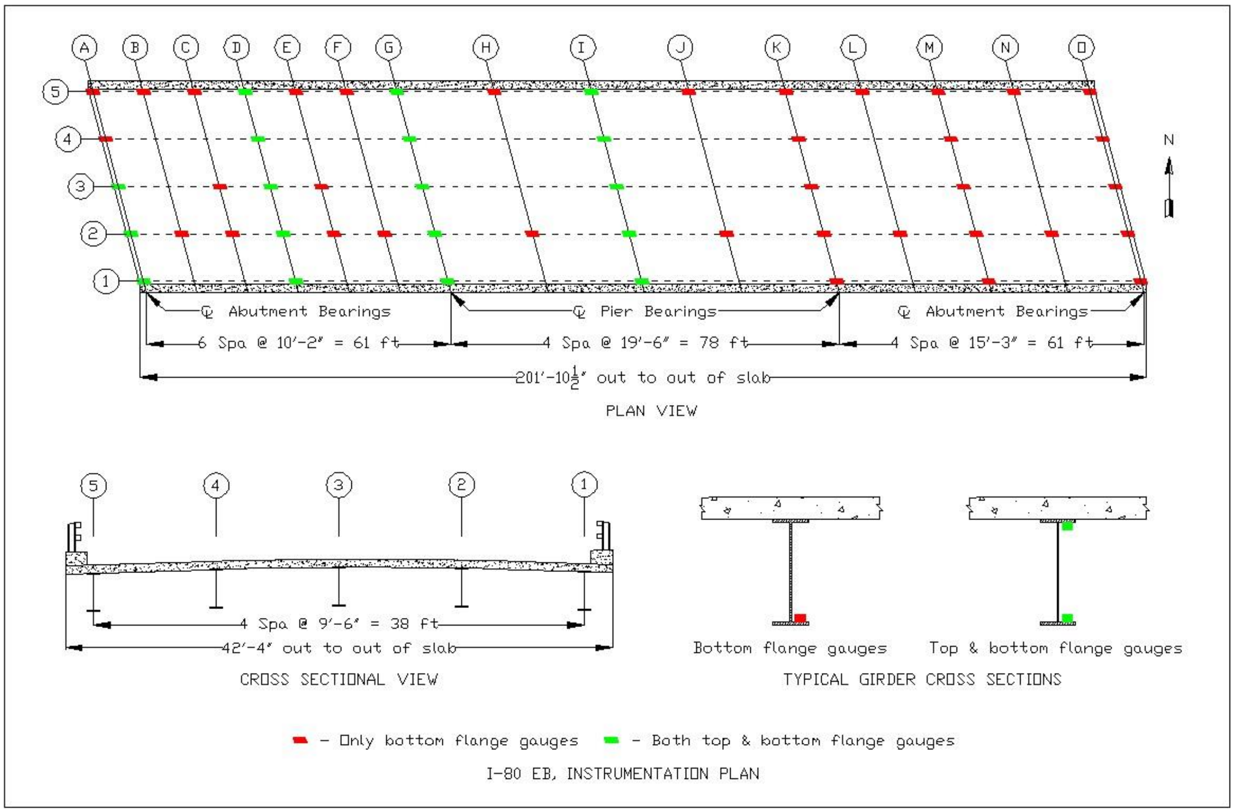


Figure 3.3. SHM system developed for the I-80 demonstration bridge

These sensors monitor the performance of the bridge. In addition, there are 8 strain gauges installed on the bottom of the concrete deck for truck detection. These sensors, in two rows of four sensors each, are located 23.59 ft and 47.34 ft from the northwestern corner of the bridge. For each row of deck gauges, there are two gauges in each lane. The sensor nomenclature is as follows and is shown in Figure 3.3.

Sensor: $X_1\ X_2\_X_3F$; Example, Sensor A1_BF (3-1)

Where

X_1 = bridge section ID
X_2 = girder line ID
X_3 = B for bottom or T for top
F = Flange

3.2 BECAS Software Architecture

The primary metrics for BECAS are strain and temperature. The data loggers typically sample sensor strain and temperature at 250 Hz (every 0.004 seconds). It should be noted that other sensors for other purposes, such as chloride infiltration, tilt, corrosion extent, acceleration, etc., can be integrated into BECAS at the request of the bridge owner or agency.

For bridge behavior changes, damage detection, and load rating computations, the quasi-static strain response of the bridge under single, five-axle truck events are used. The use of quasi-static responses assumes that vehicle inertia loads and dynamic forces are negligibly small and, therefore, that the vehicle axle loads on a bridge are the result of vehicle weight, geometry, and the stiffness of the suspension components. These computations, therefore, require filtering of the collected raw strain data for the quasi-static strain response. This is accomplished by eliminating from the raw data the other strain components by zeroing the data and using a low-pass filter (Doornink 2006, Lu et al. 2010) on the raw strain signal. The resulting quasi-static truck-strain events are further reduced to just the extrema strain values for bridge behavior assessment, culminating in bridge behavior change or damage detection and load rating. The following sections describe the functional architecture of BECAS.

3.2.1 BECAS Merge

Most BECAS installations require multiple data loggers to collect the amount and fidelity of data needed for the various downstream applications (described in the following sections). BECAS Merge creates time-sequenced data files with concatenated columns from multiple input files produced from multiple data sources. BECAS Merge performs initial data quality checking and repair associated with timestamping anomalies. Entries from multiple data sources are aligned to within 0.004 seconds or less. A screenshot of BECAS Merge during the merge process is shown in Figure 3.4.

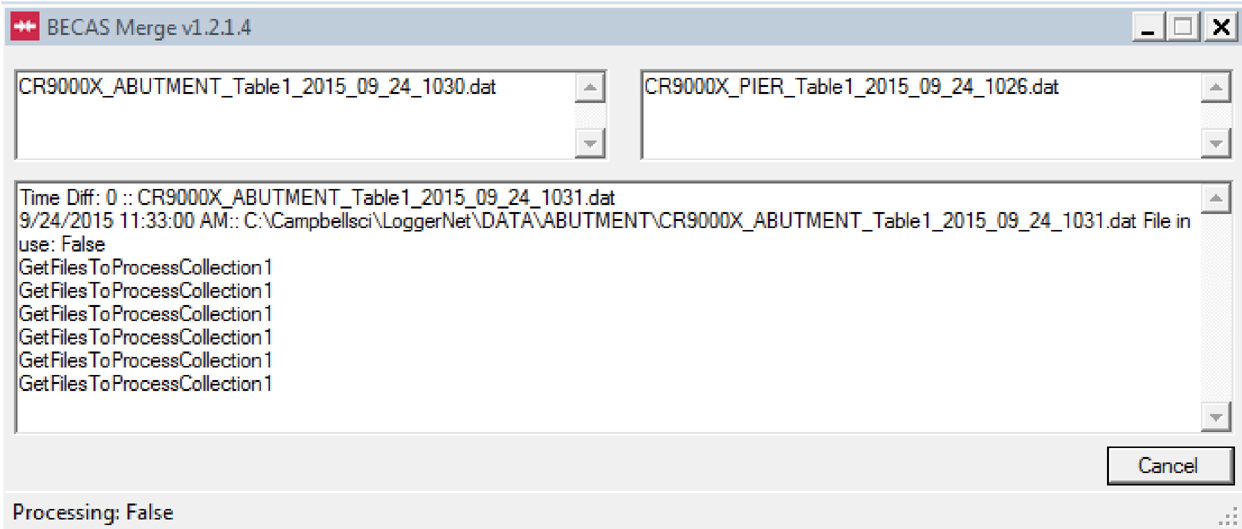


Figure 3.4. Screenshot of BECAS Merge

3.2.2 BECAS Processing Engine

The damage detection (BECAS Damage Detection) and load rating (BECAS Load Rating) algorithms require that the continuously collected data be manipulated prior to being processed further. First and foremost, it is essential that all data be of high quality. Second, the system utilizes only a subset of live load events during the damage detection and load rating processes. Although the specific loadings are user configurable, it is most common to use five-axle semi-trucks. Also, to eliminate the impact of differences in vehicle suspension systems, it is desirable to use the predicted pseudo-static response of the bridge.

The BECAS Processing Engine checks the continuous data stream for anomalies and then analyzes the time-sequenced data and evaluates those data to determine if a catastrophic event has occurred. The BECAS Processing Engine then assesses the presence of user-specified truck traffic on the bridge. The potential events are evaluated for data consistency and for the concurrency of multiple trucks on the bridge. Events that have passed integrity evaluations may then have macro-temperature effects removed, with resulting damage detection files produced.

After a user-specified number of trucks has been detected, BECAS Processing Engine passes the damage detection files to BECAS Damage Detection. Detected trucks then undergo further discrimination and discretization and strain time histories for trucks with specific user-specified characteristics, which are then passed to BECAS Load Rating. A BECAS Processing Engine screenshot is shown in Figure 3.5, an example of raw data output is shown in Figure 3.6, and an example of zeroed and filtered data is shown in Figure 3.7.

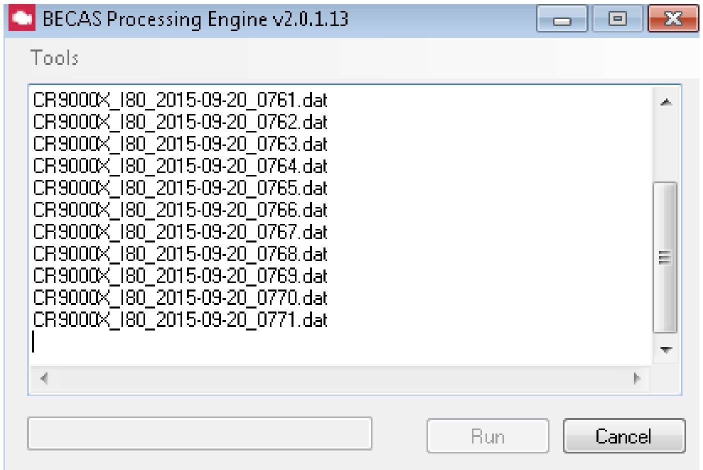


Figure 3.5. Screenshot of BECAS Processing Engine

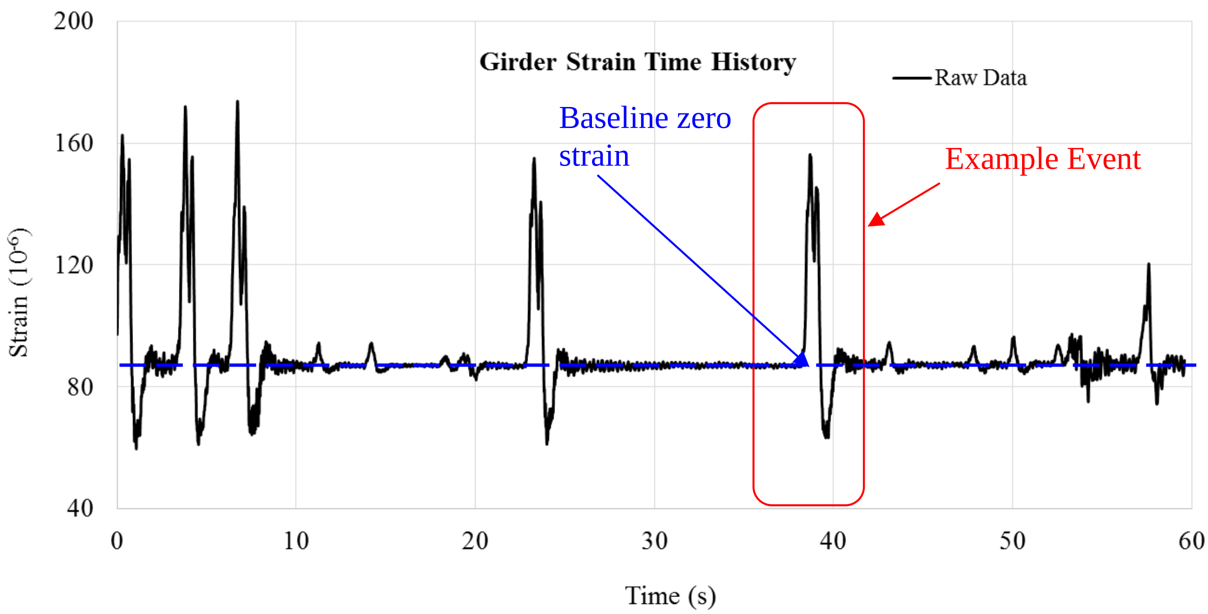


Figure 3.6. Raw data

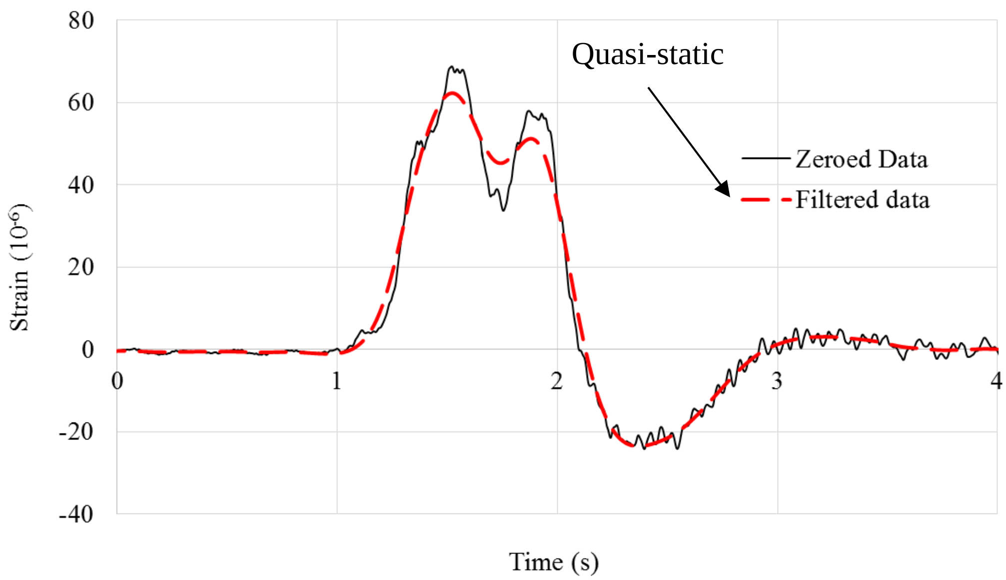


Figure 3.7. Zeroed and filtered (quasi-static) data

The key to the BECAS Damage Detection approach is the custom-developed and validated (both experimentally and analytically) data analytic approaches. Although length limitations prohibit an extremely detailed description of the approaches, the two damage detection approaches combine important aspects of structural engineering and statistics. Loosely rooted in control theory, the damage detection approach uses comparisons between current behaviors and those established during training (using BECAS Training, described below) to determine whether damage has occurred. If damage has been detected, the system then employs multiple approaches to determine the location and severity of the damage. BECAS Damage Detection applies user-specified settings established with BECAS Training to data obtained from the BECAS Processing Engine to detect changes in structural behavior and performance using a combination of statistical and/or structural tests following predefined rules. Outputs, including damage location and estimated damage levels, are output to individual files for each test and rule. End results are then packaged, and notification is sent to the authorities. A screenshot of BECAS Damage Detection is shown in Figure 3.8.

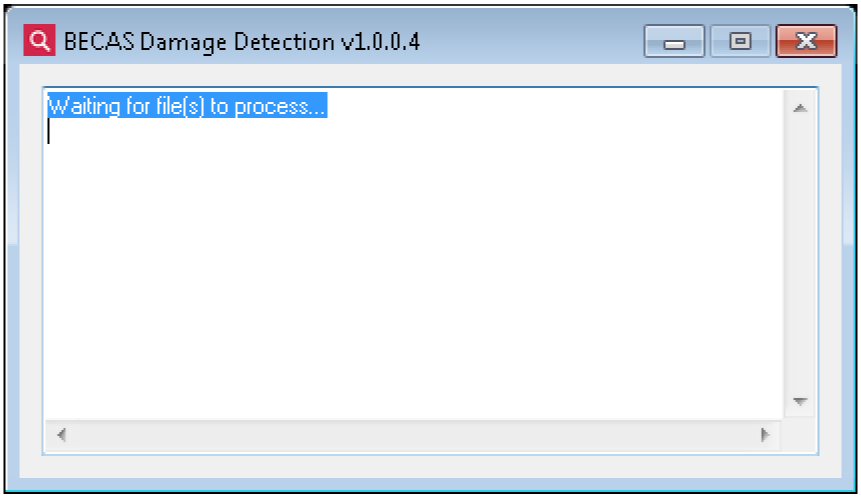


Figure 3.8. Screenshot of BECAS Damage Detection

BECAS Load Rating uses the measured response from partially known vehicles to calibrate a bridge-specific math model with geometrically/weight similar trucks selected from a specially created database. The calibrated math model is then used to calculate a bridge's safe load carrying capacity based upon user input parameters. If the estimated safe load carrying capacity is below a user-specified amount, notification is sent to authorities. A screenshot of BECAS Load Rating is shown in Figure 3.9.

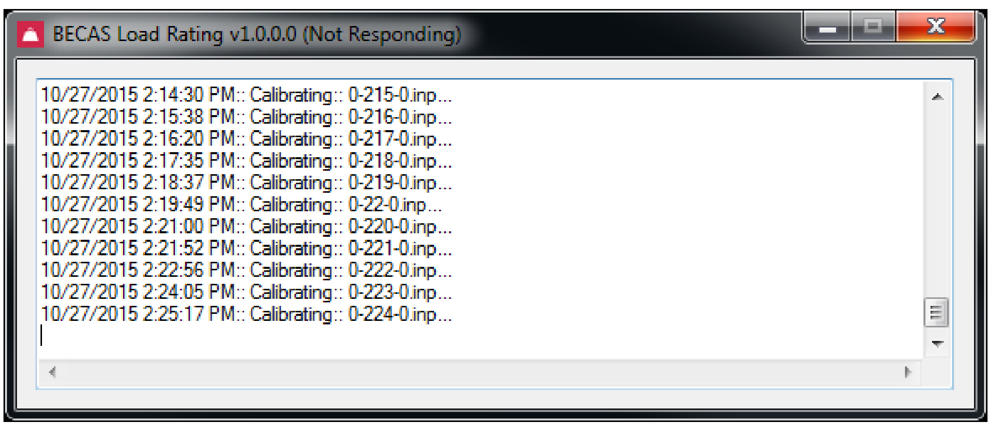


Figure 3.9. Screenshot of BECAS Load Rating

BECAS Distributor continuously monitors a specified data repository containing flat files (i.e., comma-delimited text data stored in rows). BECAS Distributor moves a specific number of files from the repository to a defined number of subdirectories (clients). BECAS Distributor continuously monitors these client folders to maintain the specific number of files. Once moved, the BECAS Processing Engines operating on each of the clients (parent and children computers) process the data and prepare the results for BECAS Damage Detection and BECAS Load Rating. Each installation of the BECAS Processing Engine has a series of checks and balances integrated such that the same files are not processed by multiple clients, nor are the results simultaneously written to the same output files.

BECAS Training is used initially to set up parts of the system (BECAS Damage Detection). This training can be at least partially completed after less than one day of system operation in some instances. BECAS Training establishes control thresholds for BECAS Damage Detection utilizing baseline data sets. Control construction approaches can, based upon user specifications, create thresholds for two custom damage detection methods. Users may set various training parameters including training size, group size, and step size, as well as select other options.

One important item to mention is that each of the applications described above has integrated communication outlets. For the most part, the system requires no routine user interaction or intervention. However, when BECAS determines that user interaction is needed, the system is configured to send out emails and/or texts to one or multiple people. When received, these communications are then quickly evaluated to determine if any immediate response is needed. For example, the previously mentioned live video camera feed might be evaluated to determine if a serious condition exists or the recorded video feed can be replayed to determine which vehicle may have caused an overload to occur.

In addition to the previously mentioned on-demand communications created by the various BECAS applications, a concise report can be generated to summarize a period of monitoring. The form of these reports was crafted to be similar to other bridge evaluation reports currently in use (e.g., National Bridge Inspection reports).

4. SHM-FACILITATED CONDITION-BASED MAINTENANCE (SHM-CBM) PRIORITIZATION SYSTEM

As stated previously, in recognition of the limitations of the state of the practice in bridge maintenance and management decision-making approaches, a new SHM-CBM maintenance prioritization system was developed in this research and is described here. With this system, maintenance priority is established using a ranking index. A higher ranking index means a lower maintenance funding priority. The ranking index is computed using both bridge inventory (NBI) data (represented by the Inventory Index) and SHM data (represented, quite simply, by a single SHM modifier, which is determined from long-term, continuous, qualitative data), as shown in Figure 4.1.

Figure 4.1. Ranking index computed using bridge inventory and SHM data

4.1 Inventory Index (II)

The Inventory Index (II) is calculated from NBI data, which are primarily obtained from biennial bridge inspections (e.g., condition ratings for different components) and codified structural analyses (e.g., inventory rating and operating rating). In many decision-making approaches, the II or another similar condition quantification mechanism plays a central role in prioritization. It should be pointed out that the II illustratively utilized here is non-specific and any numerical system can be utilized in combination with the SHM modifier (SHMM) to integrate continuous performance monitoring data into the Ranking Index. For example, the II could simply be the sufficiency rating (SR) that is directly available from NBI data. The point of the approach described below is that the SHMM allows you to alter the II based on the SHM data once it is quantified.

The SR provides a method of evaluating highway bridges by calculating four separate factors to obtain a numerical value that is indicative of a bridge's sufficiency to remain in service. The result of this method is a percentage, where 100 percent represents an entirely sufficient bridge and 0 percent represents an entirely insufficient or deficient bridge. The formula considers the structural adequacy, functional obsolescence, level of service, and essentiality for public use (FHWA 1996). The SR had been used by the FHWA and other bridge owners for many years as an important factor in determining bridge maintenance funding qualification, although it is currently not being utilized as a primary indicator.

With the introduction of the Moving Ahead for Progress in the 21st Century Act (MAP-21), a data-driven decision-making approach is now required by law. Many bridge owners are trying to modify the SR into a more agency-specific index. For example, the Iowa DOT has developed a bridge condition index (BCI). The BCI is calculated and reported in the Iowa DOT's bridge management system. Since being implemented, this index has played an important role in the Iowa DOT bridge maintenance prioritization process.

The calculation of the BCI is similar to that of the FHWA's SR but modified to be more sensitive to minor condition changes, which should allow for even more timely corrective measures to be made. Table 4.1 summarizes the major differences between the SR and the BCI.

Table 4.1. Comparison of SR and BCI calculations

	Sufficiency Rating (SR)	Bridge Condition Index (BCI)
S1	Considers the impact of load rating and condition ratings. Only the lowest rating of superstructure, substructure or culvert rating applies. Ratings above 5 are considered to be the same.	In addition to load rating, all condition ratings of deck, superstructure, substructure or culvert condition rating apply. Unlike the SR, all ratings above 2 are considered different.
S2	Considers the impact of deck condition, structural evaluation, deck geometry, underclearances, waterway adequacy, approach road alignment, roadway width, and vertical clearance. Ratings above 5 are considered to be the same.	Only considers the impact of underclearances, waterway adequacy, and roadway width (deck condition rating is covered in S1 and structural evaluation; deck geometry is a computed item).
S3 Essentiality for public use	Considers the impact of S1, S2, ADT, detour length, and whether the bridge is on the Strategic Highway Network (STRAHNET).	Same as the SR, except that the NHS highway classification is used rather than whether the bridge is on the STRAHNET.
S4	Considers the impact of detour length, structure type, and traffic safety features.	Considers the impact of fractural criticality, fatigue vulnerability, and channel protection.

As mentioned above, and as the Iowa DOT has done with the proposed SHM-CBM framework, bridge owners can easily design and implement their own to reflect an agency-specific emphasis of certain parameters.

4.2 SHM Modifier (SHMM)

Due to the relatively limited availability of SHM systems, using SHM data as a "tuning" factor rather than the dominant factor is the most practical way to implement SHM in the short term and may well be more practical over the long term as well. The continuous real-time or near-real-time SHM sensing data or derived data are fed into an equation to compute a SHMM. The SHMM is then applied as a multiplier to the II to tune its value up or down to reflect the impact of up-to-date bridge condition information and the bridge owner's opinion as to how the SHM data should affect maintenance decision making.

4.2.1 Parameters and Weighting Factors Used in the SHMM Calculation

Seven parameters (F_1 to F_7) are used in the SHMM calculation, and each parameter has a user-configurable weighting factor associated with it (γ_1 to γ_7, respectively).

$$SHMM = (F_1^{\gamma_1})\ (F_2^{\gamma_2})\ (F_3^{\gamma_3})\ (F_4^{\gamma_4})(F_5^{\gamma_5})\ (F_6^{\gamma_6})\ (F_7^{\gamma_7}) \quad (4\text{-}1)$$

Where

F_1 = Load Rating Ratio
F_2 = Load Rating Rate of Change
F_3 = Behavior Change
F_4 = Service Level Stress Rate of Change
F_5 = Service Level Stress Margin
F_6 = Expert Opinion
F_7 = Reduced Uncertainty
γ_1 to γ_7 = weighting factors associated with F_1 to F_7, respectively

The first five of the seven parameters—F_1 through F_5—are calculated from the outputs of the SHM system (i.e., Load Rating Ratio, Average Load Rating Rate of Change, Behavior Change, Service Level Stress Rate of Change, and Service Level Stress Margin). These are updated in a real-time or near-real-time fashion to reflect the most up-to-date bridge condition and performance information. The other two parameters (F_6 and F_7) are user inputs that are designed to reflect the bridge owner's opinion as to how the SHM data should affect maintenance decision making.

4.2.1.1 SHMM Parameters F_1 through F_7

- $F_{1:}$ Load Rating Ratio

$$Load\ Rating\ Ratio = \frac{Final\ Average\ Montiored\ Load\ Rating}{Codified\ Load\ Rating} \quad (4\text{-}2)$$

F_1 is the ratio of the load rating determined by using the SHM system divided by the load rating based on codified provisions. In most cases, this ratio is greater than 1.0 and, as such, demonstrates how valuable SHM data can be in accurately reflecting actual bridge behavior and performance.

- F_2: Load Rating Rate of Change = 1 + Average Load Rating Rate of Change

Average Load Rating Rate of Change is an output of the SHM system. It reflects the general trend in bridge capacity change, including both magnitude and rate of change over time. Due to structural deterioration, the value of the Average Load Rating Rate of Change is, in general, expected to be negative with a very small absolute value.

F_2 is defined as 1+ Average Load Rating Rate of Change. For example, in the demonstration application that follows, the Average Load Rating Rate of Change since system installation is -0.3%. F_2 is, therefore, calculated as 99.7%. A factor smaller than 1.0 would be applied in the SHMM calculation to reduce the final ranking index and reflect the gain in maintenance priority due to the decrease in structural capacity.

- F_3: Behavior Change

The F_3 parameter reflects how much the system performance is deviating from its baseline performance. Using the BECAS system, this parameter is defined as one minus the smaller value of the violation rates calculated from the F-test and the strain range method. A higher violation rate indicates a more significant deviation from the system's baseline level, and, as a result, a higher maintenance priority should be assigned. For example, when the violation rate is 2%, the Behavior Change parameter (F_3) would be 98%. This value is always less than or equal to 1.

- F_4: Service Level Stress Rate of Change = 1 - Service Level Stress Rate of Change

Service Level Stress Rate of Change is an output of the SHM system that indicates the change trend in measured maximum strain (i.e., maximum strain in each minute). It could be either positive or negative, and, in general, its absolute value is small. A positive value means the service stress level is going up, and, therefore, a higher maintenance priority is appropriate, and vice versa.

- F_5: Service Level Stress Margin

$$Service\ Level\ Stress\ Margin = \frac{Codified\ Strain\ of\ HS20\ with\ impact}{Max\ Monitored\ Strain} \qquad (4\text{-}3)$$

F_5 is a measure of how the predicted service level strain compares with the measured strains. A value greater than 1.0 indicates that the designed live load strain is higher than the monitored service level live load strain. A larger value indicates that the structural system has a higher live load capacity reserve, and therefore a lower maintenance priority can be assigned.

- F_6: Expert Opinion (1.25)

The F_6 parameter is used to allow a trained SHM engineer to provide an expert analysis of all of the collected data, which can then be used to increase or decrease the maintenance priority. In an operational sense, the expert opinion factor would be determined by the organization preparing an annual summary report based on the collected data.

- F_7: Reduced Uncertainty (Default Value 1/0.85)

By using the real-time or near-real-time bridge condition/performance data collected by a SHM system in maintenance decision making, the uncertainty of bridge performance is reduced. This factor is applied to offset the uncertainties introduced during codified calculation.

4.2.1.2 Use of the Weighting Factors γ_1 to γ_7

A weighting factor value can be applied to each of the F_1 to F_7 parameters to reflect the priorities of an individual agency. In some ways, this can be considered as representing the values of the agency. For example, if capacity is the highest priority, the weighting factor values for the capacity-related parameters can be adjusted to reflect that.

In the demonstration application that follows in Section 4.3, the value of γ_1 is set to 1.0 (as shown in the right-hand column of Table 4.3 in that section). This reflects a baseline value of the weighting factor and indicates that the user wants to take full advantage of the factor of F_1. A weighting factor higher than 1.0 indicates a higher maintenance decision making impact, while 0 means that the user does not want that specific factor to play any role in decision making.

In the demonstration application, γ_2 through γ_4 are set to 2 (as shown in the right-hand column of Table 4.3 that follows) because F_2, F_3, and F_4 all represent long-term global changes to a structure. Their impacts on maintenance decision making are profound. The values of F_2 through F_4 are typically stable and close to 1.0. However, any significant change in these parameter values indicates sizable structural performance changes that should be given significant attention.

When one parameter value is significantly larger than others, to prevent it from overwhelmingly affecting the final ranking index, a smaller weighting factor should be assigned to it. In the demonstration application, γ_5 is set to 0.2 (as shown in the right-hand column of Table 4.3 that follows) to roughly normalize its impact to be equivalent to the impact of F_7.

4.2.2 Use of the SHHM Calculation

The combination of quantitative data and user configurability with the calculation for the SHMM (Equation 4-1) allows an owner agency to customize its approach to meet agency goals.

A product equation rather than a summation equation is used in the SHMM calculation for two major reasons. The first reason is that all of the factors used in the calculation are ratios or percentages instead of differences. The second reason is that research has shown that simple multiplication can avoid the complicated normalization procedure for each factor and still keep the final ranking reasonable (Tofallis 2014).

The physical meaning and typical values of F_1 to F_7 and γ_1 to γ_7 were discussed in the previous section. The computed SHMM is then applied as a modifier in the computation of the ranking index to show the impacts of SHM. For bridges without an SHM system installed, the SHMM has a value of one. By comparing ranking indexes among bridges, the condition-based maintenance priorities are established.

4.3 Demonstration Application

As a demonstration, an Excel spreadsheet was developed using 21 bridges from the Iowa bridge inventory. Twenty of the bridges are not configured using the BECAS SHM system, and one bridge has the SHM system available (the I-80 Sugar Creek Bridge, FHWA #22380). In this application, IIs are obtained from NBI data, and the SHMM is calculated with the inputs from the SHM system and the user-configurable weighting factors.

For the II, the user has the opportunity to select either SR or BCI. Either of these is directly importable from the NBI data and has a value between 0 and 100 for any bridge. Table 4.2 and Figure 4.2 present the SR and BCI for each of the 21 bridges. As can be seen from Figure 4.2, the SR and BCI share similar change trends.

Table 4.2. SR and BCI of all 21 bridges

Bridge Index	FHWA #	SR	BCI
1	3410	48.40	47.40
2	3825	57.00	40.70
3	3826	58.80	51.20
4	4111	88.80	78.80
5	4271	99.30	92.20
6	7901	80.10	69.60
7	7911	79.40	59.30
8	12411	85.00	80.90
9	12491	96.90	81.10
10	12511	98.20	84.20
11	12920	74.40	60.70
12	12970	42.70	43.50
13	12980	68.60	55.20
14	12990	68.10	57.20
15	13010	46.70	92.90
16	13040	61.50	59.70
17	13050	74.80	61.10
18	13060	74.10	64.60
19	13101	97.00	85.10
20	13111	97.00	84.10
21	22380	96.30	70.00

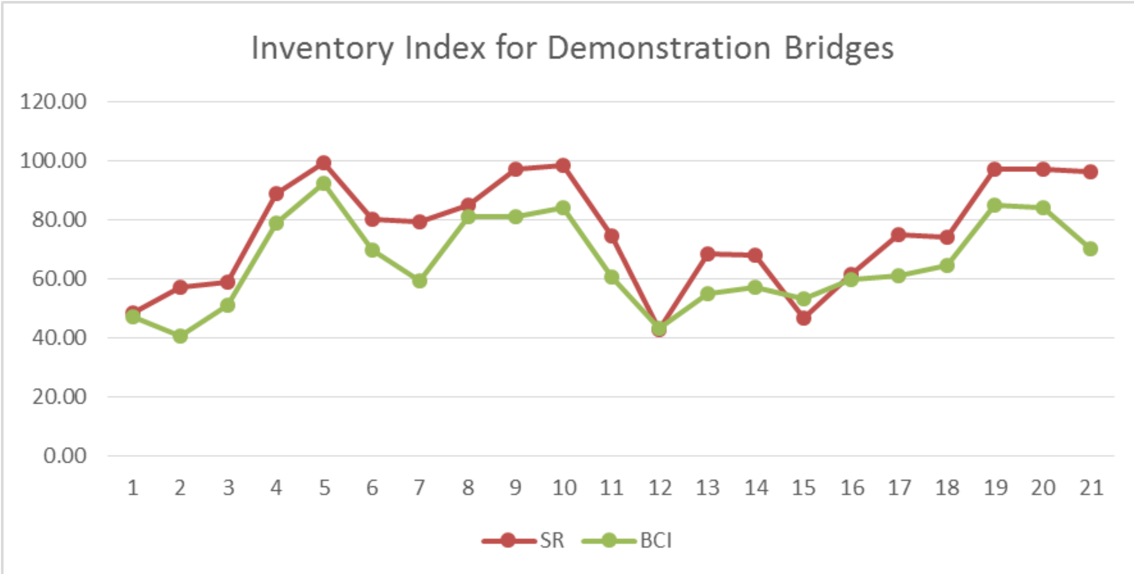


Figure 4.2. SR and BCI of all 21 demonstration bridges

For the 20 bridges without SHM instrumentation, the SHMM is simply 1.0. That means that the maintenance priorities of the bridges are totally determined by bridge inventory data.

For the instrumented bridge (FHWA #22380), the SHMM is calculated by using the SHM input data, which are represented by F_1 to F_5, along with the user inputs for F_6 (Expert Opinion parameter) and F_7 (Reduced Uncertainty parameter). A snapshot of the values of F_1 to F_5 (which are updated in real-time or near-real-time) and typical values of F_6 and F_7 for the demonstration bridge are shown in Table 4.3. The values of the weighting factors that are associated with F_1 to F_7 are also presented in Table 4.3 in the right-hand column.

Table 4.3. Values of F_1 to F_7 used in SHMM computation for bridge FHWA#22380

Parameters	Value	Weighting Factor
F_1 (Load Rating Ratio)	1.37	1
F_2 (Load Rating Rate of Change)	0.997	2
F_3 (Behavior Change)	0.98	2
F_4 (Service Level Stress Rate of Change)	1.000001	2
F_5 (Service Level Stress Margin)	1.68	0.2
F_6 (Expert Opinion)	1.25	1
F_7 (Reduced Uncertainty)	1.18	1

F_1 (Load Rating Ratio) = 1.37 indicates that at the specific time, the monitored load rating is 37% higher than the codified load rating. In the SHMM computation, any factor with a value larger than one will potentially increase the final raking index and thereby reduce the maintenance priority. F_1 is used here to reflect the maintenance priority impact caused by the monitored live load capacity. A weighting factor of 1 is used for F_1 to show that the extra live load capacity gained from SHM should be fully used in maintenance decision making.

F_2 (Load Rating Rate of Change) = 0. 997. The monitored load rating has decreased by 0.3% annually since the SHM system was installed, and F_2 is calculated as 1 - 0.3% = 0.997. The generally decreasing trend in load rating indicates an increasing demand for maintenance. The value slightly smaller than 1 is applied to show this impact.

F_3 (Behavior Change) = 0.98 because the maximum strain range violation rate is 2% since the installation of the system. This violation rate of 2% is the smaller of the violation rates obtained from different violation rules. A higher violation rate indicates a more significant deviation of the structural performance from its baseline (i.e., as-designed performance), and therefore a higher maintenance priority is required.

F_4 (Service Level Stress Rate of Change) = 1.000001 because the measured maximum strain of each minute for the control location (D2_BF) has been decreasing at a rate of 10^{-6} since the system was installed. The decreasing trend in live load effect indicates a decreasing demand for bridge maintenance.

The values of F_2 to F_4 are typically stable and close to one. But once any of the factors show a significant change, it is an indication of a significant structural change, and therefore more attention should be paid to maintenance decision making. Values larger than one are more appropriate for γ_2 to γ_4. In this demonstration application, values of 2 are used.

F_5 (Service Level Stress Margin) = 1.68 indicates that the codified HS20 strain at the control location is 68% higher than the monitored maximum strain. This factor measures the margin between the strain produced by the HS20 truck and the maximum strain to which the bridge has been exposed. A larger value indicates a larger capacity reservation and, therefore, that a longer service life can be expected, and the maintenance priority can be lowered. The value of F_5 can be large and can drop significantly due to a single event, so a relatively smaller weight factor is appropriate. The value of 0.2 is used here to roughly normalize its impact to the same level of F_7.

F_6 (Expert Opinion) and F_7 (Reduced Uncertainty) are two user input parameters in this system. Values of 1.25 and 1.18 are used, respectively, in this demonstration application. The Expert Opinion parameter was set at 1.25 after reviewing all available data and making an expert assessment of bridge performance. The value of the Reduced Uncertainty parameter was set to 1/0.85 (1.18) to offset the uncertainties introduced during codified calculation. Weighting factors of 1 are used for these two parameters.

Using the values of F_1 to F_7 and γ_1 to γ_7 shown previously in Table 4.3, the SHMM and the final ranking index are summarized in Table 4.4.

Table 4.4. Ranking index with $\gamma_{1,6,7} = 1$, γ_2 to $\gamma_4 = 2$, and $\gamma_5 = 0.2$

	SR	BCI
FHWA #22380	96.30	70.00
SHMM	2.14	2.14
Ranking index	206.08	149.80

A ranking index higher than 100 indicates that the replacement priority of the bridge is lower than that of the bridges with an SR or BCI equal to 100.

Tables 4.5 and 4.6 show bridge age data as related to the SR and the BCI of the bridge

Table 4.5. SR and corresponding bridge age

SR	Average Bridge Age	Std Dev
96.30	38.6	8.1
100	18.1	12.6

Table 4.6. BCI and corresponding bridge age

BCI	Average Bridge Age	Std Dev
70.00	39.1	15.2
100	2	0

The average age for bridges with SR = 100 is 18.1 years, and the average age is 38.6 when SR = 96.3. When the bridge's ranking index increases from 96.3 (without SHM) to > 100 (with SHM), the equivalent bridge age is reduced by at least 20 years. That may mean that bridge replacement can be postponed by 20 years because the bridge is performing notably better than expected. Similarly, when the BCI is used as the II, results show that bridge replacement may be able to be postponed by 37 years.

The service life extension obtained from this demonstration application is used in the next chapter to financially justify the cost of installing SHM instrumentation.

5. FINANCIAL JUSTIFICATION FOR BRIDGE SHM AND A CASE STUDY

The cost-effectiveness of any SHM system is important for promoting wider adoption of this relatively new technology. The cost of SHM sensors, installation, system development, and operation may seem expensive initially. However, if the benefits gained from SHM instrumentation are taken into account, the cost justification is not difficult to understand. These benefits include the following:

- Extend the bridge service life by knowing its true performance
- Reduce bridge maintenance costs
- Prevent bridge collapse

For this chapter, the researchers performed a lifecycle cost analysis by comparing the annual cost for a bridge with and without SHM instrumentation. As a case study, the I-80 Sugar Creek Bridge system was analyzed and documented.

5.1 Lifecycle Cost Analysis (AASHTO 2016)

5.1.1 Cost of SHM Installation

It is not always easy to estimate the cost of implementing a SHM solution. The following list can help establish the primary costs that are usually associated with an SHM implementation (AASHTO 2010).

Immediate costs/initial costs:

- SHM system design
- Hardware costs
- Installation costs
- Cost for preparing installation documentation and system manuals

Operational costs:

- System maintenance: spare parts, consumables, energy, and communication costs
- Data management costs
- Data analysis, interpretation, and reporting costs

5.1.2 Benefits of SHM Solutions

Some benefits gained from SHM can easily be quantified as dollar values and are called hard benefits. Hard benefits include immediate or deferred cost savings that are derived from the extension of bridge service life, postponed maintenance activities, and the prevention of bridge collapse, etc. However, there are other benefits that are harder to quantify. An SHM system is still perceived as a “high-tech” addition to any structure where it might be implemented, whether it be a building, bridge, or tunnel. This addition can, therefore, project a positive image of the owner or designer implementing the system or reassure the public about the safety of a new or aging structure. These benefits are called soft benefits.

Some benefits are a mix of hard and soft benefits, such as the reduction of risk. On the one hand, implementation of SHM leads to a reduction of perceived risk and increased public satisfaction. From this perspective, the benefits are soft. On the other hand, the reduction of risk has been built into our algorithm for computing service life extension. This benefit is hard. In the future, the reduced risk may potentially lead to a reduction in other costs, which is another hard benefit.

For this study, only hard benefits were used to study the cost-effectiveness of SHM implementation. More specifically, the benefits of extending bridge service life, postponing maintenance activities, and preventing bridge collapse were considered in this study.

5.1.2.1 Extension of Bridge Service Life

Many structures are in much better condition than expected. In these cases, monitoring enables an actual increase in the safety margins for the bridges without any intervention on their structures. Taking advantage of better material properties, original over-design, and the synergetic effects, it is often possible to safely extend the lifetime or load-bearing capacity of a structure without any intervention.

The algorithm developed for this project that quantifies the service life extension of a bridge with SHM instrumentation was discussed in Chapter 4, and the results are used in this cost analysis.

5.1.2.2 Postponing Maintenance Activities

The implementation of SHM solutions offers the possibility of changing the maintenance paradigm from preventive or corrective maintenance to condition-based maintenance. Therefore, maintenance can be done at the most effective time. Due to a lack of specific information on how much SHM can delay maintenance activities and in the interest of brevity, we have assumed that all maintenance activities can be postponed by five years. This delay in maintenance activities is believed to be conservative and is derived from the owner’s ability to evaluate the quantitative performance of each bridge objectively.

5.1.2.3 Preventing Bridge Collapse

The failure rate of bridges in the US was studied for AASHTO (2005) using historical failure data. The results showed that the probability of bridge collapse is 1/4,700 annually. Based on the data extrapolation and a 95% confidence interval, the estimated average annual bridge collapse rate in the US is between 87 and 222, with an expected value of 128. Historical data show that loss of life occurred in about 4% of bridge collapses. In total, the cost of a bridge collapse would include the following:

- Cleanup
- Rebuild the bridge
- Human injury and loss of life
- Property loss (e.g., vehicle damage)
- Detour costs:
  - Operating costs
  - Detour time costs

5.1.3 Lifecycle Cost Analysis to Justify SHM Installation

Lifecycle cost can be expressed as the equivalent present value of costs or the equivalent uniform annual costs using compound interest formulas. For this study, the uniform annual cost method was used in the cost-benefit analysis to evaluate the adoption of SHM instrumentation. To do this, cash flow needs to be defined and appropriate interest formulas need to be applied.

5.1.3.1 Maintenance Profile and Cash Flow

In bridge projects, cash flow is typically associated with bridge construction and/or maintenance activities. The maintenance profile of a bridge, which includes maintenance events, the times at which the events occurred, and the number of occurrences of each event, must be defined before the lifecycle cost analysis can be performed. Although it is not uncommon for the predefined maintenance profile to be modified during the bridge service life, it still provides a good estimate of expected future costs. Figure 5.1 shows a bridge maintenance profile and the associated cash flow. Figure 5.2 shows the cash flow for an SHM installation.

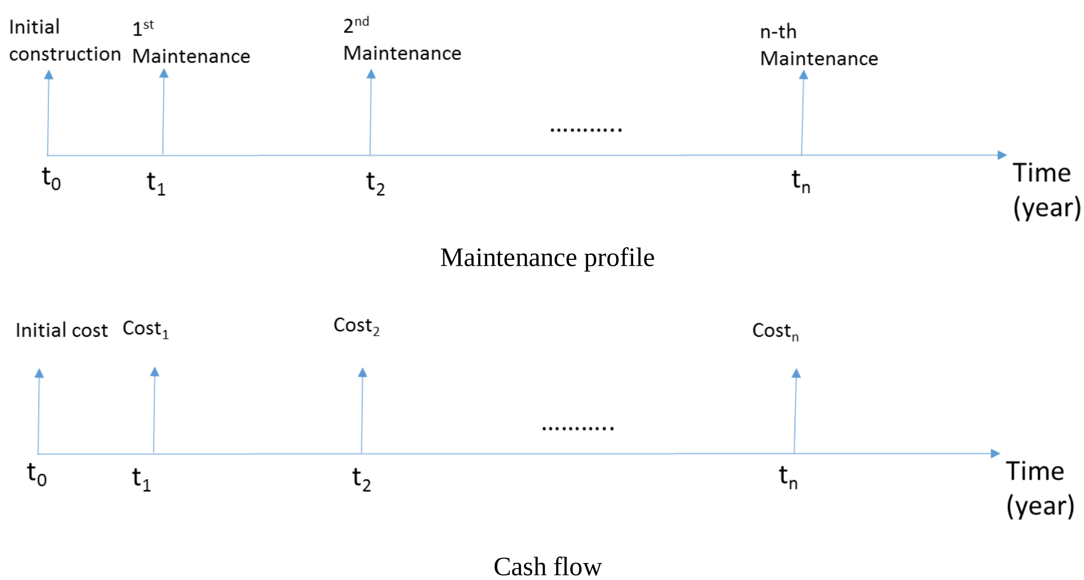


Figure 5.1. Bridge maintenance profile and associated cash flow

Figure 5.2. Cash flow for an SHM system

5.1.3.2 Interest Formula: Nominal Interest, True Interest, Inflation, and Future/Present Value

Classical engineering economic evaluation methodology, for the most part, ignores the effects of inflation. The relationship between future value and present value is shown in Equation 5-1.

$$P = \frac{F}{(1+i)^n} \quad (5\text{-}1)$$

Where

P = present sum of money ($)
F = future sum of money ($)
^{n} = number of interest period
i = interest rate per period (%)

The rationale for this approach is that if inflation affects all aspects of cash flow in the same manner, its net effect on economic decision making is nil (Aktan et al. 1998). In public works, this is not always true.

Funds for bridge construction and maintenance at both the state and federal levels are derived primarily from fixed cents-per-gallon motor fuel taxes. Revenues may increase as fuel consumption increases, and inflation rates are relatively low. Funding in this case likely keeps pace with costs. However, fuel consumption may not always increase. As alternative fuel sources emerge and are adopted and more energy efficient cars are purchased and put into service, a reduction in gasoline consumption is possible, leading to a reduction in gas tax revenue. In the meantime, inflation keeps increasing the costs for bridge construction and/or maintenance. In this situation, where the rate of inflation outpaces the rate of income in program funding, inflation may affect investment decisions and must be taken into account. The interest rate under this situation can be expressed as the so-called "true" interest rate and is calculated as follows:

$$True\ Interest\ Rate(i^*) = \frac{(1+i_0)(1+p)}{(1+f)} - 1 \quad (5\text{-}2)$$

Where

i_0 = nominal interest rate
f = inflation rate
p = funding increase rate

When the rate of increase in funding keeps pace with the rate of inflation (i.e., $p = f$), the true interest rate equals the nominal interest rate. In this project, p is taken as zero and therefore i^* is different from i_0, as in the following:

$$i^* = \frac{(1+i_0)}{(1+f)} - 1 \qquad (5\text{-}3)$$

Any event with a present price of X would have a future price of $X(1+f)^n$ when inflation is considered. Its equivalent present cost is $X((1+f)^n \div (1+i_0)^n)$, which is $X \div (1+i^*)^n$.

$$P = X\frac{(1+f)^n}{(1+i)^n} \qquad (5\text{-}4)$$

Where

P = present value of a future event
X = present price for this event
n = event occurrence year

That is why, in some literature, X is called the constant price and is used along with the true interest rate. To avoid confusion, the nominal interest rate and the inflation rate along with inflated prices are used in this project. Hereafter, i is used to represent the nominal interest rate.

Note that, due to inflation and the cost of money, the present cost of a future event does not necessarily equal its present price.

5.2.3.2.2 Annual Cost

Equation 5-5 calculates the present value of the cost for a single cycle of a bridge's life.

$$A = I.C. + P_1 + P_2 + \ldots + P_n \qquad (5\text{-}5)$$

Where

A = present value of the total cost for a bridge during its entire service life
$I.C.$ = initial construction cost
P_1 to P_n = present value of maintenance activities

P_1 to P_n are calculated using present price, inflation rate, and nominal interest rate using Equation 5-4. When the service lives of two alternative bridges are different, the annual costs of unlimited lifecycles (i.e., repeating the same maintenance profile an unlimited number of times) should be used as an alternative analysis. Figure 5.3 presents the cash flow of a bridge for unlimited lifecycles, in which *n* is the bridge's service life for a single cycle and *m* is the number of cycles, which is taken to be unlimited in this analysis.

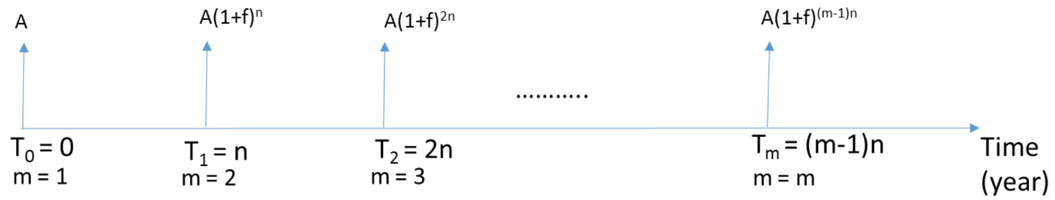


Figure 5.3. Cash flow for unlimited lifecycles

The present value for an unlimited number of lifecycles is calculated as follows:

$$C \ = \ A \ + A\frac{(1+f)^n}{(1+i)^n} + A\frac{(1+f)^{2n}}{(1+i)^{2n}} + \cdots A\frac{(1+f)^{(m-1)n}}{(1+i)^{(m-1)n}} = A\frac{(\frac{1+i}{1+f})^n - \frac{1}{(\frac{1+i}{1+f})^{(m-1)n}}}{(\frac{1+i}{1+f})^n - 1} \qquad (5\text{-}6)$$

From the definition of $i*$, the above equation can be simplified as Equation 5-8.

$$C = A\frac{\left[(1+i^*)^n - \frac{1}{(1+i^*)^{(m-1)n}}\right]}{[(1+i^*)^n - 1]} \qquad (5\text{-}7)$$

$$a = C\frac{[i(1+i)^{mn}]}{[(1+i)^{mn} - 1]} \qquad (5\text{-}8)$$

Where

C = current value of the total cost for *m* cycles of bridge service life
A = current value of the total cost for a bridge during its first service lifecycle
a = annual cost
n = service life
m = number of service lifecycles
$i*$ = true discount rate
i = nominal interest rate

When $m \rightarrow \infty$ in Equation 5-7, the item of $\frac{1}{(1+i^*)^{(m-1)n}} \rightarrow 0$, and, when $\frac{[(1+i)^{mn}]}{[(1+i)^{mn}-1]} \rightarrow 1$ in Equation 5-8, the two equations can be rewritten as follows:

$$C = A\frac{[(1+i^{*})^{n}]}{[(1+i^{*})^{n}-1]} \tag{5-9}$$

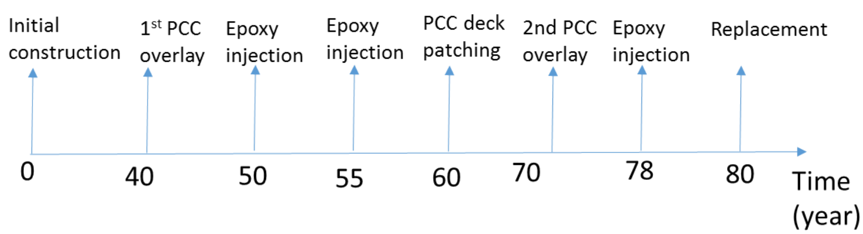
$$a = (C)(i) \tag{5-10}$$

Once the annual costs for the baseline bridge and the SHM-instrumented alternative bridge are computed, they are compared to determine the cost savings. The SHM system is economically beneficial when the cost savings are higher than the cost of SHM installation. As an example, the I-80 Sugar Creek Bridge SHM system was studied and is presented in the next section.

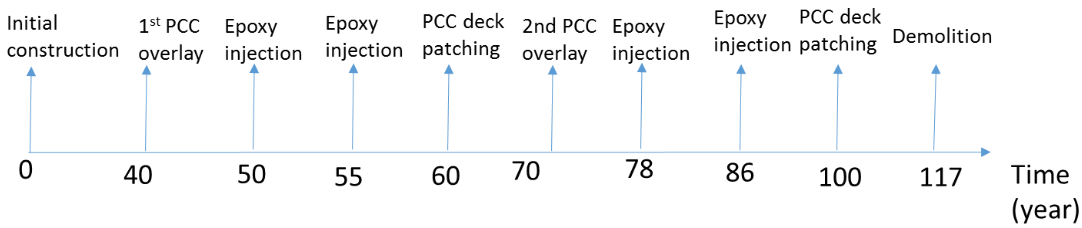
5.2 Case Study (Financial Justification for I-80 Sugar Creek Bridge SHM System)

5.2.1 Maintenance Profiles for Bridges with and without SHM Instrumentation

For this study, Bridge 0 was used to represent the baseline bridge (without a SHM system); Bridge 1 is the same bridge but with the BECAS SHM system installed. The service life of Bridge 1 is 37 years longer than that of Bridge 0 using the BCI as the II (see Chapter 4). The timing for each maintenance activity is assumed to be normally distributed, with the mean shown in Figure 5.4 and a standard deviation of 5 years.



Bridge 0



Bridge 1

Figure 5.4. Maintenance profile and associated cash flow for bridges with and without SHM instrumentation

With SHM installed, it is assumed that all maintenance activities are postponed by 5 years during the baseline service life. Extra maintenance activities are scheduled for the extra service life. The maintenance activities, the times at which the activities occurred, and the quantities of the work are summarized in Tables 5.1 and 5.2.

Table 5.1. Maintenance profile for Bridge 0 (baseline bridge)

Activity	Age at Occurrence	Deck Percentage
Initial construction (IC)	0	100%
1st PCC overlay	N(40,5)	100%
Epoxy injection	N(50,5)	10%
Epoxy injection	N(55,5)	10%
PCC deck patching	N(60,5)	7%
2ndt PCC overlay	N(70,5)	100%
Epoxy injection	N(78,5)	10%
Demolition0	N(80,5)	100%

Table 5.2. Maintenance profile for Bridge 1 (service life extended by 37 years)

Activity	Age at Occurrence	Deck Percentage
Initial construction (IC)	0	100%
1st PCC overlay	N(45,5)	100%
Epoxy injection	N(55,5)	10%
Epoxy injection	N(60,5)	10%
PCC deck patching	N(65,5)	7%
2ndt PCC overlay	N(75,5)	100%
Epoxy injection	N(83,5)	10%
Epoxy injection	N(90,5)	10%
PCC deck patching	N(100,5)	30%
Demolition1	demolition0+37	100%

5.2.2 Prices for Maintenance Activities

The cost for each maintenance activity is shown in Table 5.3.

Table 5.3. Prices for maintenance activities

Activity	Cost ($/ft^2)
Initial construction (IC)	N(250,50)
PCC overlay	N(45,5)
Epoxy injection	6
PCC deck patching	N(60,5)
Demolition	10% of IC

Data used here are from Aktan et al. (1998) and Iowa DOT experience

Notice that the costs shown in Table 5.3 are present costs. Whenever an event is a future event, it needs to be converted to the future cost by considering inflation and then converting the cost back to the present worth to include the impact of the cost of money (see Equation 5-4).

5.2.3 Annual Cost Savings from Service Life Extension

An interest rate of 3.5% (Aktan et al. 1996) and an inflation rate of 1.6% (value for October 2016 from Arangio 2012) are used along with the maintenance profile presented in Section 5.1.3.1 and the present price shown in Section 5.1.3.2 to calculate the annual costs for Bridge 0 and Bridge 1. First, the present cost for one lifecycle is computed using Equations 5-5 and 5-6 This figure is then plugged into Equations 5-7 and 5-8 to obtain the annual cost for unlimited lifecycles. The computed mean of annual costs is summarized in Table 5.4. The cost savings are about $13,400 dollars/year.

Table 5.4. Mean of the annual cost for Bridge 0, Bridge 1

	Bridge 0	Bridge 1
Total current value (in thousands of dollars)	105.57	92.17
Cost savings (in thousands of dollars)		13.39

5.2.4 Annual Cost Savings from Maintenance Postponement

With an SHM system in place, it is possible that certain types of maintenance activities can be postponed. For this study, it was assumed that the maintenance activities are postponed by 5 years due to knowledge of the true performance of the structure through real-time monitoring. This increases the annual cost savings by about $1,000 per year.

5.2.5 Annual Cost Savings from Preventing Bridge Collapse

5.2.5.1 Injury and Vehicle Damage Cost

As mentioned in Section 5.1.1.3 on Preventing Bridge Collapse, the probability of a bridge collapse is 1/4,700, and 4% of the collapses involve a loss of life (AASHTO 2005). For this study, it was assumed that each bridge collapse leads to either two lives lost or 10 injuries and one damaged vehicle. The average costs per injury or per damaged vehicle used here are from a study conducted by Benedettini et al. (2009). The values are converted to 2016 equivalent values using a discount rate of 3% (see Table 5.5). The annual costs of injury and vehicle damage are computed to be about $4,790 per year.

Table 5.5. Comprehensive unit costs for each injury or damaged vehicle in 2010 and 2016 values

Injury Type	Comprehensive Unit Costs in 2010	Comprehensive Unit Costs in 2016
Fatal	9,145,998	10,920,799.92
MAIS5 (critical injury)	5,579,614	6,662,350.91
MAIS4 (severe injury)	2,432,091	2,904,043.84
MAIS3 (serious injury)	987,624	1,179,274.71
MAIS2 (moderate injury)	396,613	473,576.66
MAIS1 (minor injury)	41,051	49,017.04
MAIS0 (no injury)	2,843	3,394.69
PDO (damaged vehicle)	3,862	4,611.43

5.2.5.2 Cleanup and Rebuild Costs

Cleanup of the failed bridge is assumed to cost 10% of the bridge's construction cost. In the I-80 case study, cleanup and reconstruction will cost approximately $2.2 million. Considering the probability of a bridge collapse, the costs saved from intervention are about $469 per year.

5.2.5.3 Detour Cost

The detour cost has two major parts: the operating cost and the time cost. It is assumed that reconstruction of the bridge will take approximately one year. Based on bridge inventory data, the ADT of this bridge is 20,100, and 22% of the total ADT is trucks. This is equivalent to 5.7 million car trips and 1.6 million truck trips per year. The operating cost per mile, value of time per person-hour, and standard occupancy rates are taken from a reference (Bonnin-Pascual and Ortiz 2014) and converted to 2016 values, as shown in Table 5.6, using a 3% discount rate.

Table 5.6. Operating cost, time cost, and standard occupancy rate

	2013		2016	
Cost or Rate Type	Per mile for autos ($)	Per mile for trucks ($)	Per mile for autos ($)	Per mile for autos ($)
Operating cost per mile	0.20	1.10	0.22	1.20
Time per person-hour	11.42	22.44	12.48	24.52
Standard occupancy rate	1.1	1.0		

The detour length is assumed to be three miles. Additionally, the detour time is assumed to be five minutes. The detour cost is computed to be about $4,131 per year.

With the information described above, the total annual cost for a bridge collapse is summarized in Table 5.7 as about $9,400 per year.

Table 5.7. Total cost for bridge collapse

Category	Cost ($)	Probability	Cost with Probability ($)
Vehicle damage	4611.43	0.0213%	0.98
Injury cost	22,536,526.33	0.0204%	4,603.21
Life loss cost	21,841,599.83	0.0009%	185.89
Reconstruction	2,200,000.00	0.0213%	468.09
Annual detour cost	19,416,108.17	0.0213%	4,131.09
Total	**65,998,845.76**		**9,389.24**

5.2.6 Costs of the SHM System

The initial installation cost of the demonstration SHM system is $119,410, and the annual operation cost is estimated to be $15,970. These figures cover all of the costs listed in Section 5.1. Converting the total cost to an annual cost results in a cost of $20,700 per year for an average service life of 117 years.

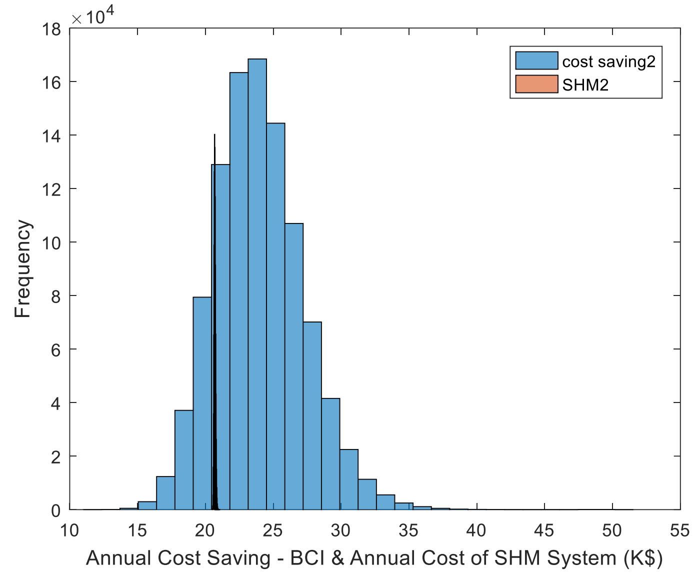
Table 5.8 summarizes the mean of the cost savings gained from the SHM system and the annual costs of the SHM installation.

Table 5.8. Mean of the annual cost savings and the annual costs of SHM installation

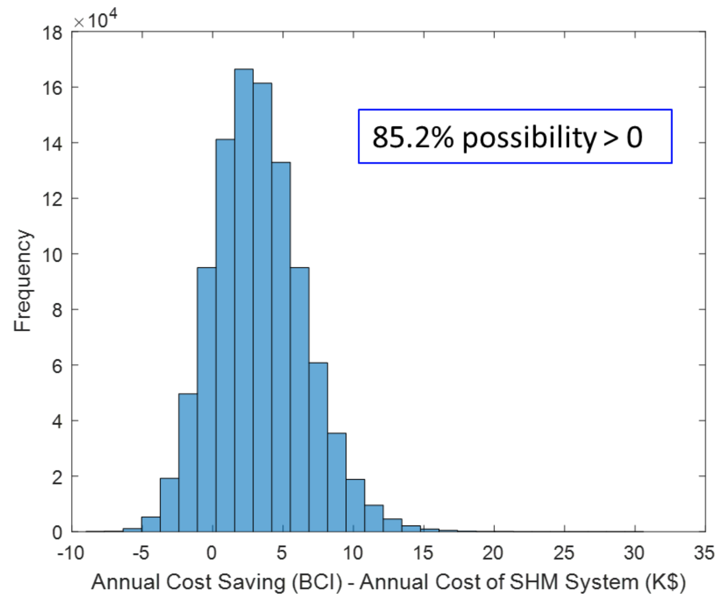
Cost Savings (thousands of dollars)				
Service Life Extension	**Postponed Maintenance**	**Bridge Collapse Prevention**	**Total**	**Cost of SHM (thousands of dollars)**
13.4	1.0	9.4	23.8	20.7

5.2.7 Cost-Benefit Analysis with Monte Carlo Simulation

The price and time of the occurrence of each maintenance activity are not fixed numbers and can vary from those assumed above. To study the impact of these variations, normal distributions were assumed for the parameters important for the economic analysis, as shown in Tables 5.1 through 5.3. In addition, a Monte Carlo simulation was performed with 1,000,000 iterations. Figure 5.5 presents the cost savings—including service life extension, maintenance postponement, and the cost of bridge collapse prevention—in comparison to the costs of the SHM installation.



Cost savings and SHM cost for 37-year service life extension



Difference of cost savings and SHM cost for 37-year service life extension

Figure 5.5. Annual cost savings and annual cost of SHM

The figure shows that the SHM cost can be justified 85.2% of the time when the bridge's service life is extended by 37 years.

6. SUMMARY AND DISCUSSION

6.1 Summary

This report presents a framework for the implementation of a structural health monitoring-facilitated condition-based maintenance (SHM-CBM) prioritization system. This system can be realized by integrating the real-time or near-real-time SHM data into most currently used statewide bridge maintenance and management practices.

Currently, most bridge owners prioritize maintenance funding using either a corrective maintenance or preventative maintenance approach. Sometimes these two approaches are combined using engineering judgement to achieve a certain level of optimization. However, this type of optimization may be too subjective, and the strategy may lead to either too little maintenance or over-maintenance.

In light of the limitations of the state of the practice in bridge maintenance and management decision-making approaches, a new SHM-CBM maintenance prioritization system was developed with this research. With the CBM approach, maintenance is performed only when it is needed and at the most opportune times. This maintenance strategy is still very new to the bridge management community. In fact, not until the development of bridge SHM systems could the CBM strategy be implemented because bridge inventory data are not sufficient to implement such strategies.

In the proposed SHM-CBM system, the maintenance funding priority is measured using a ranking index. A higher ranking index means a lower maintenance funding priority. The ranking index is computed by using both NBI data (i.e., II) and SHM data (i.e., SHMM) and is defined as the II multiplied by the SHMM. Three major steps are involved in the calculation of the ranking index:

1. Import the II from the NBI data. This index represents the bridge condition evaluation obtained from biennial bridge inspections and the AASHTO codified structural analysis.

2. Calculate the SHMM. The SHMM represents modifications to the bridge's condition based on continuous and near-real-time health monitoring data.

3. Combine the II and the SHMM into a ranking index that indicates the maintenance priority.

As a demonstration, the ranking index was used in the service life study of the I-80 Sugar Creek Bridge, with results showing that the bridge's service life can be extended by up to 37 years.

Bridge service life extension, along with other benefits gained from SHM instrumentation (e.g., postponed maintenance and prevention of bridge collapse), were quantified as dollar values and used in the cost-benefit analysis to justify the adoption of the SHM solution.

6.2 Advantages of the System

Compared to the current state of the practice for bridge maintenance decision making, this approach has the following advantages:

- Continuous and near-real-time SHM data are used in maintenance decision making.

- CBM can potentially prevent over-maintenance caused by preventive maintenance and prevent the severe consequences of non-optimized maintenance decisions caused by corrective maintenance.

- Uncertainty about structural performance is reduced with SHM inputs. By knowing the true performance of a bridge in real-time or near-real-time, bridge collapse can be effectively prevented and bridge service life can be extended without extra maintenance efforts.

- Given the benefits of SHM, such as extended bridge service life, postponed maintenance activities, and prevented bridge collapse, bridge SHM is cost-effective.

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